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A COMPARISON OF MANUALLY DIGITIZED RADAR DATA AND OBSERVED COOL SEASON PRECIPITATION OVER THE SOUTHERN APPALACHIANS

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ABSTRACT

A limited evaluation of observed precipitation and precipitation estimates utilizing manually digitized radar (MDR) values over the southern Appalachians and adjacent plains (foothills) was undertaken for the period mid-November 1973 through mid-February 1974. Factors such as beam filling, range, precipitation tops, freezing level, terrain effects, frequency distribution of MDR data, and radar estimates of precipitation over mountain and plain are examined.

1. INTRODUCTION

Frequently, 2 to 5 in (51 to 127 mm) rainfall amounts, associated with stratiform precipitation, are reported from mountain locations. These amounts are accompanied by relatively low manually digitized radar (MDR) totals (Moore, et al., 1974) when compared with similar precipitation amounts from non-mountain areas. Some of the difference is related to the precipitation-producing mechanism. A study was undertaken to examine the effect of mountainous terrain on precipitation rate estimates from radar data.

2. DATA

The initial investigation was undertaken for the area covered by the northern half of the Athens, Georgia (AHN) MDR grid and was later extended to include the area covered by the Bristol, Tennessee (TRI) MDR grid. The average number of precipitation gage-to-radar (gage/radar) comparisons per grid square was 170 for AHN and 105 for TRI. The AHN radar is located in rolling terrain about 50 nm (93 km) southeast of the southern end of the Appalachians at an elevation of 860 ft (262 m) msl. The TRI radar is located at an elevation of 4274 ft (1303 m) atop a mountain. The TRI radar is equipped with a video integrator and processor.

Seven widespread rain events were selected for the cool season precipitation study. Six of the cases were evaluated for the entire precipitation period. The remaining case was a 24-hour episode from an extended precipitation period. Four warm season episodes were examined but are only briefly mentioned because of the small size of the data sample and the differing precipitation mechanism. All the gages in the AHN MDR grid (Fig. 1) recorded measurable precipitation in all the cases. Some gage data were missing during some of the cases studied. The southern portion of the AHN MDR grid was not included in the gage/radar study due to the sparsity of gages - only one or two per grid square. The gage density per grid square (MDR squares are approximately 40 nm [75 km] square) ranged from two to seven in the AHN MDR study area and from two to six for TRI MDR grid squares. One gage was located on a grid boundary and was utilized in two grid squares.

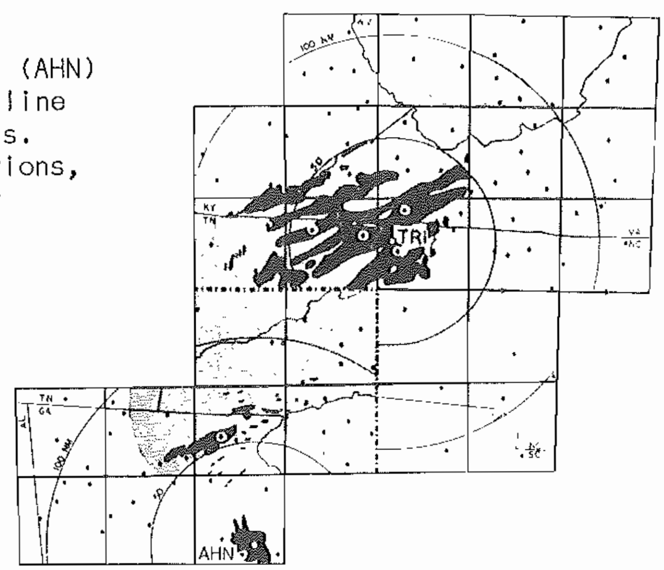
Precipitation values were obtained from published Hourly Precipitation Data for the respective state. Hourly precipitation amounts for each gage were tabulated for each grid square and the maximum gage catch was categorized and compared with the rainfall category derived from the hourly MDR value using Table I.

Table I. Manually Digitized Radar (MDR) Code

Code No.	Coverage in Grid Square	Intensity Category	Rainfall Rate	
			in/hr	mm/hr
0				
1	any VIP 1	Weak	<.1	< 2.5
2	≤1/2 of VIP 2	Moderate	.1-.5	2.5-12.7
3	>1/2 of VIP 2			
4	≤1/2 of VIP 3	Strong	.5-1	12.7-25.4
5	>1/2 of VIP 3			
6	≤1/2 of VIP 3 and 4	Very Strong	1-2	25.4-50.8
7	>1/2 of VIP 3 and 4			
8	≤1/2 of VIP 3,4,5,6	Intense or Extreme	> 2	>50.8
9	>1/2 of VIP 3,4,5,6			

Precipitation was recorded in tenths of an inch for several gages and values of .10 in (2.5 mm) were considered MDR I for this study. The MDR value is a nearly instantaneous coded value of the maximum precipitation rate in the grid square and is determined by the radar operator near H+30 each hour. This value is not expected to have a hand-in-glove relationship to observed precipitation. Throughout this paper it should be kept in mind that operational use of the MDR/gage relationship must be in a probabilistic framework; the "snap-shot" observations do not differentiate between a rain cell crossing some portions of the 1600 nm^2 area of a grid square and rain persisting over an area for the full hour. Grid square locations in the following discussion are by row and column, i.e., the lower left grid square in Fig. I would be referred to as AHN 31.

Fig. I. MDR grid for Athens, Ga. (AHN) and Bristol, Tn. (TRI), broken line separates station coverage areas. Hourly precipitation gage locations, small dots. Ground clutter for each radar, solid areas. Approximate mountainous area indicated by stippling.



3. DISCUSSION

Fig. 1 shows the location of the radars and the MDR grid squares. The locations of precipitation gages are indicated by dots. Stippling indicates areas with frequent elevations about 2,000 ft (615 m). For this study mountain grid squares are those containing stippling, the remainder are considered plains. The normal ground clutter present on the radar scope is depicted by solid dark areas. At times considerably more ground clutter is present.

Ground clutter increases the problem of evaluating precipitation returns on the radar scope. The antenna elevation angle must sometimes be increased when precipitation and ground clutter are coincident, consequently beam overshooting is increased. MDR data, however, are taken with 0.5° antenna elevation angle. Mountain-located radars have a built-in overshoot due to their elevation, and lowering the elevation angle of the antenna only increases the ground clutter. The poorer gage/radar comparisons for the grid squares containing the radars (Figs. 2 and 3) are related to these ground clutter problems.

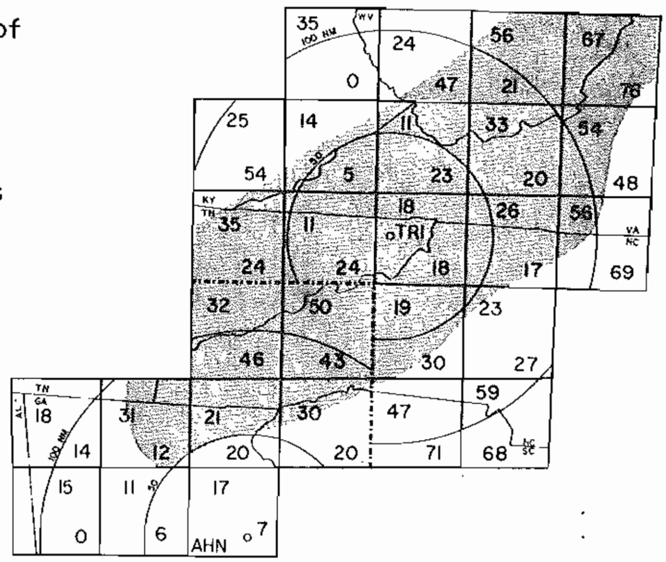


Fig. 2. Upper number - percentage of hours measurable precipitation was observed somewhere in the grid square and MDR values for the same hour were zero. Lower number - percentage of hours observed precipitation amounts exceeded the indicated radar precipitation rate category. For the lower number, only hours when ALL gages in the grid square reported measurable precipitation were considered. Data are for the seven cool season cases.

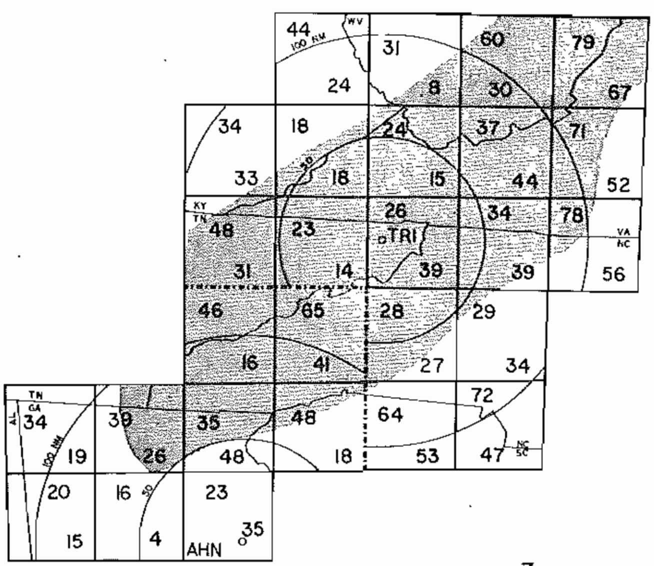


Fig. 3. Percentage of hours measurable precipitation was observed somewhere in the grid square and this amount exceeded the MDR indicated precipitation amount by one or more categories. Upper number - cool season cases, lower number - warm season cases.

Beam filling is no doubt a significant factor in gage/radar disparities. As the cross-sectional area of the 2° radar beam increases with increasir range (and, consequently, transmitted energy per unit cross-sectional area decreases) meteorological targets of a given size reflect decreasing amounts of energy with increasing range. The deterioration of the gage/radar comparison with increasing range is evident in Figs. 2 and 3. Note that over mountainous areas precipitation is often observed more than twice as frequently as indicated by radar at ranges beyond 100 nm (185 km). An examination of AHN MDR values for mountain and plain grid squares during the cool season when precipitation was widespread (lower numbers, Fig. 2) shows that on the average radar estimates of precipitation rates were low by one or more precipitation categories 28% of the hours for mountain grid squares and 7% for plains grid squares. Fig. 3 shows that when measurable precipitation was reported somewhere in the grid square during the hour, the mountain and plain averages were 47% and 23%, respectively. The same figure shows the gage/radar disparity when precipitation was observed somewhere in the grid square during the hour for the four warm season precipitation events. Note that the ground clutter problem is still very evident even though convective precipitation dominates.

Relatively low echo tops are often associated with widespread stratiform precipitation during the cool season. Thus, the beam filling problem is enhanced and becomes acute beyond about 70 nm (130 km). An effort was made to compare precipitation tops with differences in gage catch and radar precipitation rate estimates. It should be pointed out that the reconstruction of precipitation top information over an area from radar records yields at best a poor estimate. Because of this it was done only for 5,000 ft (1524 m) intervals. It was found that precipitation tops 25,000 ft (7620 m) and above occurred in about 15% of the hours studied. This group accounted for only 1% of the hours in which the gage/radar disparity was at least one category. Tops were below 20,000 ft (6096 m) 56% of the hours and accounted for nearly 80% of the gage/radar differences. Other recent gage/radar studies have examined the problems caused by beam elevation. Wilson and Pollock (1974) found it necessary to adjust radar estimates of precipitation at 100 nm (185 km) by factors ranging from about two to seven over the Lake Ontario watershed during hurricane Agnes.

The gage/radar differences, again only for the AHN grid area, were examined in relationship to AHN freezing level data for the various precipitation cases. Snow was extensive during the latter portion of one event but accumulation was light. Snow was also a small factor during a portion of another event. The mean freezing level for the two snow-related cases was 7,500 ft (2286 m) msl, while the freezing level for the other five cases averaged 11,000 ft (3353 m). The number of hours when the observed and radar-estimated precipitation amounts differed by one or more categories showed a 5% increase during the snow-related events for the mountainous grid squares but in plains squares differences occurred twice as often as compared with the non-snow events.

For hours when precipitation was observed within the square the maximum hourly gage catch for each grid square was categorized according to the coincident MDR precipitation estimate for squares over the mountains and plains during the five non-snow periods. The average maximum observed hourly precipitation and the frequency of occurrence for each category are shown in Table 2. Note, for example, that for mountain squares 26% of the hours had MDR 0 and the average maximum precipitation for these squares and these hours was .06 in (1.5 mm).

Table 2. Comparison of Average Maximum Observed Precipitation (in) and Frequency of Occurrence with Coincident MDR Precipitation Rate

	MDR Precipitation Rate Category (in/hr)									
	No Echoes		Light		Moderate		Heavy		Very Heavy	
			.01 - .10		.10 - .50		.50 - 1.0		1.0 - 2.0	
Mountains	.06	26	.15	31	.23	31	.36	9	.43	3
Plains	.05	11	.08	35	.18	36	.38	12	.40	6

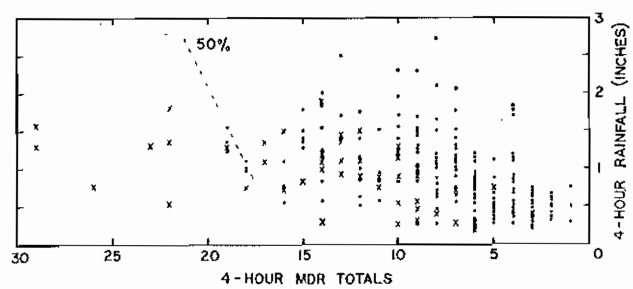
It can be seen from Table 2 that most of the differences between mountain and plain radar precipitation estimates result from a higher frequency of non-detection of precipitation and from underestimating light and moderate precipitation rates over mountainous areas. When precipitation was occurring somewhere in the grid square, MDR 0 (no precipitation) was reported more than twice as frequently for mountain squares as for plains squares. The average maximum hourly precipitation amount for mountain grid squares for MDR 1 (light precipitation) was nearly twice the plains squares amount and 30% more than the plains squares amount for MDR 2 (moderate precipitation).

The observed maximum precipitation for almost half of the hours in the light precipitation rate category (MDR observation) exceeded .10 in (2.5 mm) for the mountain grid squares. A check of those hours when .50 in (12.7 mm) or more precipitation was observed (i.e., the precipitation rate was "heavy" or "very heavy") showed that radar-indicated rainfall rates were moderate or less 56% of those hours for mountain grid squares, and 27% for plains grid squares. These data suggest that radar observations may result in sizable underestimates of precipitation over mountainous areas under certain conditions.

Average storm totals (average of all gages in a grid square) for mountain and plain grid squares were compared (AHN area only) for the cool season cases. Given the same MDR total, 67% more precipitation was observed over a mountain grid square than over a plains grid square. When the maximum storm total for each grid square was selected from the cool season cases and averaged for mountain and plain grid squares, two-and-one-half times more precipitation resulted from the same MDR total for a mountain grid square than for a plains square. Maximum storm totals for individual mountain and plain grid squares were compared for the same precipitation episode and the maximum difference was selected. In this instance the same MDR total showed a maximum precipitation total for a mountain grid square eight times larger than the plains square total.

Four-hour precipitation amounts and four-hour MDR totals for the AHN MDR grid area are compared for mountains and plains in Fig. 4. Only four-hour periods when all gages in a grid square reported measurable precipitation during all four hours were utilized and the maximum single station total in the square is plotted. The nomogram given by Moore, et. al (1974, p 17) for estimating rainfall amounts from MDR totals was used to determine the 50% probability of occurrence line in Fig. 4. Ideally, the data would be evenly distributed about the 50% line. While this is the case with the plains data, the mountain data are skewed to the low side. If four-hour MDR totals for mountain grid squares are doubled prior to entering the nomogram, the resulting maximum precipitation estimates compare more favorably with observed precipitation amounts. However, the wide range of precipitation totals associated with four-hour totals of ten or less for mountainous grid squares makes this somewhat impractical.

Fig. 4. Comparison of 4-hour MDR totals and precipitation amounts for gages in mountainous MDR grid squares (●) and plains grid squares (X), AHN MDR area. Only 4-hour periods when all gages in a grid square reported measurable precipitation were utilized. Dashed line is the 50% probability of occurrence from the nomogram used to estimate precipitation amounts from MDR values (Moore, et. al 1974, p 17).



Flooding (stream above flood stage) was associated with the largest four-hour MDR totals in plain (Atlanta) and mountain (Greenville, South Carolina) grid squares in Fig. 4; the precipitation being of a convective nature. The maximum observed four-hour precipitation was under 2 in (51 mm) in these cases. Two precipitation episodes produced four-hour precipitation totals of 2 in (51 mm) or more over mountain grid squares and these rains were accompanied by four-hour MDR totals ranging from 7 to 14. One of these episodes produced flooding (Rosman, North Carolina) and was associated with a maximum four-hour MDR total of 10. The maximum observed storm total for this flood event was 7.86 in (200 mm), of which 5.45 in (138 mm) fell in a nine-hour period and was accompanied by a nine-hour MDR total of 15. A large spatial variation in precipitation was evident in this grid square with the minimum observed storm total being 0.6 in (15 mm).

Table 3 shows the effects of range and terrain on the frequency of occurrence of categories of four-hour MDR totals for the months of December 1973, and January 1974. Mountainous grid squares for this investigation included those shown in Fig. 1 for AHN and TRI and the squares immediately west of TRI 31 and AHN 11. The plains area is three grid squares wide and extends to the west, southwest and south of the mountain grid squares. Range to the center of each grid square was determined and MDR data were tabulated in 20 nm (37 km) increments for mountain and plain grid squares. The data base, 21,000 non-zero, four-hour grid square totals, included MDR data from radars located at Nashville, Tennessee, and Centreville, Alabama, in addition to AHN and TRI. An "F" in a category indicates the maximum four-hour MDR total in a grid square prior to a stream rising above flood stage as reported in the Flood Stage Data National Summary. It must be remembered, of course, that although short-term rainfall, for example, four-hour amounts, is considered of major significance in flash-flood forecasting, antecedent conditions play an important role.

Table 3. Frequency (%) Comparison of Non-Zero Four-Hour MDR Totals
December 1973 - January 1974

	Distance From Radar to Center of MDR Grid Square											
Four-hour MDR Total	20 nm (37 km)		40 nm (74 km)		60 nm (111 km)		80 nm (148 km)		100 nm (185 km)		120 nm (222 km)	140 nm (259 km)
	Mtn	Pln	Mtn	Pln	Mtn	Pln	Mtn	Pln	Mtn	Pln	Mtn	Mtn
32-35				*				*				
28-31				*		*F		*				
24-27		1F		1		*	*	*		*		
20-23		2		2	*F	1F	*	1		*		
16-19		3		3F	1	3	1	4		1		
12-15	3	4F	1	6F	3	6	2	4		3		
8-11	9	12	9	11	9F	12	10F	11F	2F	8F		
4-7	45	40	47	37	45	39	44	37	34	40	16	23F
1-3	42	37	44	40	42	39	43	44	64	48	84	77
Hrs with no echoes (%)	67	65	68	65	69	67	71	73	77	75	81	97
2° beam width	4200 1300		8500 2600		12500 3800		17000 5200		21000 6400		25500 7800	30000 ft 9200 m
Beam axis altitude, 0.5° elevation	1000 300		2500 800		5000 1500		9000 2700		12000 3700		16500 5000	21500 ft 6600 m

*less than 0.5%

Nearly half of the flood producing precipitation was associated with maximum four-hour MDR totals less than 12. These relatively low totals make the recognition of a developing flood threat from persistent stratiform precipitation, which is characteristic of the cool season, very difficult. The smaller range in MDR totals compounds the problem for mountainous areas where maximum four-hour MDR totals were 8 to 12 below those for plains grid squares. The occurrence of four-hour MDR totals of 20 or more for plains grid squares exceeded the frequency of occurrence for mountain grid squares by a factor of twelve. Mountain occurrences of MDR totals of 20 or more were all in grid squares AHN 22 and AHN 24 which are only partially mountainous. The maximum four-hour MDR total for a mountain grid square (AHN 22) was 26 and was associated with deep convection and did not meet the widespread precipitation criteria used in Fig. 4. If MDR totals for grid squares AHN 22, 23 and 24 are deleted from the mountain group, all four-hour MDR totals would be less than 16. A check of a smaller summer sample of four-hour MDR totals (12,000) shows only a 30% increase of MDR totals of 20 or more for plains grid squares over mountainous squares. Table 3 also shows the percent of hours with no echoes for squares at various ranges. As expected, the percentages generally increase with increasing range. Radar beam width and elevation above the ground are also shown as a function of range.

4. SUMMARY

This investigation points out the difficulty in recognizing significant precipitation events solely from radar estimates of precipitation rates over mountainous areas during stratiform precipitation episodes. The orographic enhancement of stratiform precipitation does not take place through a sufficiently deep layer to be adequately detected by present operational radar techniques. When precipitation tops are near or below 20,000 ft (6096 m), radar estimates of precipitation amounts are significantly below those observed over mountainous areas. This effect is not limited to the cool season and is also evident over the plains, although to a lesser degree.

It has not been the purpose of this paper to discuss the many factors affecting the radar reflectivity factor such as number, size, shape, and composition of precipitation particles. However, it should be noted that changes in particle size distribution may have relatively small effects on precipitation content and rainfall rate, but a rather large effect on the reflectivity factor. Blanchard (1953), for example, pointed out that orographic rain in Hawaii contains few drops with diameters larger than .06 in (1.5 mm) yet the rainfall rate may exceed 4 in hr^{-1} (100 mm hr^{-1}). Numerous researchers have indicated that the Z/R relationship, the basis for estimating rainfall rate from radar reflectivity, is a function of the nature of the precipitation - stratiform, orographic, thunderstorm, etc. (see, for example, Battan, 1973, pp 88-97).

Aside from such considerations in the present study, it should also be noted that with "snap-shot", once-per-hour radar observations the same MDR four-hour total will be associated with more rainfall where there are orographic controls "anchoring" the precipitation features than where such features are simply passing over the area.

The value of radar intelligence in locating areas of persistent precipitation over mountains remains high although somewhat limited as range increases. The problem of non-detection of stratiform precipitation over mountainous areas could be improved by implementing the procedures, or a variation thereof, currently employed to detect snow. With computer processing of raw radar data becoming more prevalent, it would be advantageous to develop seasonal and regional adjustments tailored to local problems so that estimates of precipitation rates would be more accurate.

The effect of ground clutter on radar detection of precipitation is not limited to stratiform precipitation situations. The incorporation of terrain suppression circuitry, common on ARTCC radars (Fuertsch, 1973), might alleviate the terrain problem. An evaluation of precipitation estimates using digitized radar data from the broad beam (in the vertical) ARTCC radar and that from the narrow beam WSR-57 radar over mountain and plains would be of value.

Significant differences in maximum precipitation estimates using radar intelligence exist between mountainous areas and adjacent plains. Maximum storm total precipitation over mountainous areas is frequently four to five times the amount over plains areas for the same MDR total. If the findings of Wilson and Pollock are applicable to the present area of study, radar estimates of maximum storm precipitation over mountainous areas beyond 100 nm (185 km) could be low by a factor as large as fifteen.

Due to the large spatial variation of precipitation the real time use of rain gages to adjust radar precipitation estimates in mountainous areas even in stratiform precipitation situations must be limited to the gage vicinity. Also, considering the myopic character of the radar especially during stratiform precipitation episodes, reliance on radar to fill gaps between conventional observation stations in mountainous areas should be carried out with extreme caution. A radar report of "No Echoes" does not guarantee "No Precipitation."

Acknowledgment. The author wishes to thank the staff of Scientific Services Division, National Weather Service Southern Region Headquarters for providing hourly and four-hour totals of MDR data. Thanks to the staff of WSO, Bristol, Tennessee, for their assistance. Special thanks to G. C. Holladay and the staff of WSO, Athens for their valuable comments and discussion.

(over)

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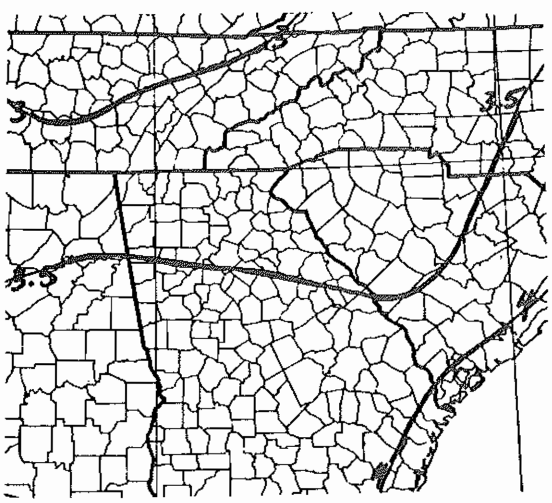
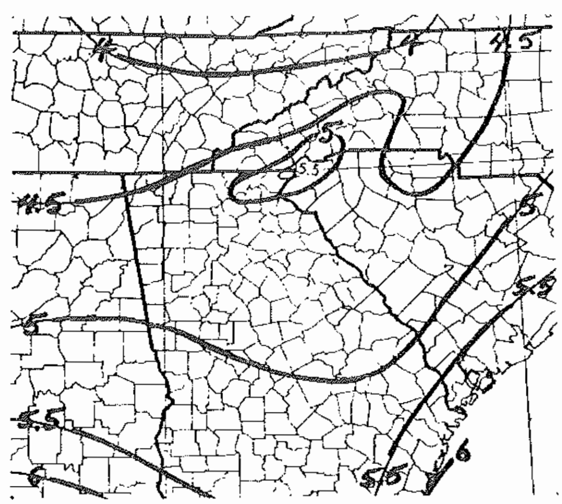
Editor's note:

The area studied in this project includes a unique heavy-rainfall frequency maximum. The following Figs. (a) and (b) give return-period estimates (in inches) for 100-year 1-hour and 3-hour rainfall, respectively.* The presence of the marked singularity in (b) may bear some relationship to the discussion on page 2 of the "snapshot" nature of the radar observations and the tendency for persistence of precipitation over orographic "anchors".

(a)



(b)



*From Technical Paper No. 40, "Rainfall Frequency Atlas of the U.S.", U.S. Department of Commerce, Weather Bureau, Washington, D.C. 1961.